An Ocean Observing System for Large-Scale Monitoring and Mapping of Noise Throughout the Stellwagen Bank National Marine Sanctuary

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LONG-TERM GOALS

The project goals are to map the low-frequency (<1000 Hz) ocean noise budget throughout the Stellwagen Bank National Marine Sanctuary (SBNMS) ecosystem, identify and quantify the contributing sources of anthropogenic sounds within that ecosystem, and determine whether or not

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14. ABSTRACT
The project goals are to map the low-frequency (<1000 Hz) ocean noise budget throughout the Stellwagen Bank National Marine Sanctuary (SBNMS) ecosystem, identify and quantify the contributing sources of anthropogenic sounds within that ecosystem, and determine whether or not such noises have the potential to impact endangered marine mammals and fishes that use the Sanctuary.

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such noises have the potential to impact endangered marine mammals and fishes that use the Sanctuary.

OBJECTIVES

This project represents a high-level, integrative 'bench mark' study aimed at characterizing the marine acoustic environment and the health of an urbanized, productive ecosystem, SBNMS. The primary products will be a suite of tools designed to be transferable to other ecological regions and an extensive database specific to the project. These will include both mechanisms for data collection and analysis as well as a conceptual framework for integrating and interpreting the scientific results.

APPROACH

Well-established passive acoustic technologies and a mixture of existing and newly-developed analytical methods are applied to meet the goals of this project. Arrays of Marine Autonomous Recording Units (MARUs), deployed since December 2007, are gathering low-frequency acoustic data within the sanctuary for a continuous 30 month period. MARU data are used to calculate the spatial and temporal variability of the noise field and to detect and localize vocally active baleen whales and fish species. This project has developed methodologies that combine MARU data with commercial ship track data from the US Coast Guard's Automatic Identification System (AIS) to calculate the noise budget contributions from vessels within and outside the sanctuary. Data on the distributions and acoustic behaviors of ships and marine animals are merged in order to investigate the potential for ocean noise to mask animal sounds and/or otherwise impact vocally-active species. These data are input into tools either as modifications to the Acoustic Integration Model/AIM (Frankel et al. 2003) or as Matlab plug-ins that interface with an open-source sound analysis platform called XBAT (http://xbat.org/home.html; Figueroa 2008). Additionally, data from visual sighting efforts and digital tags (Johnson & Tyack 2003) placed on individual humpback whales are used to improve parameter values of whale distribution, 3-D whale movements and behavioral responses.

This study is co-managed by Cornell University Laboratory of Ornithology's Bioacoustics Research Program (Cornell), NOAA Fisheries' Northeast Fisheries Science Center (NEFSC) and NOAA NOS's Stellwagen Bank National Marine Sanctuary (SBNMS). Dr. Christopher Clark's team at Cornell supply calibrated MARUs, synchronize acoustic data files, and develop analysis tools for quantifying and mapping ocean noise. Dimitri Ponirakis is a central member of the Cornell analysis team. Dr. William Ellison and Dr. Adam Frankel at Marine Acoustic Inc. collaborate with Cornell to upgrade AIM for vessel noise and total noise spatio-temporal calculations and mapping. Dr. Sofie Van Parijs oversees NEFSC's project responsibilities, including refurbishment of MARUs, partial staffing of field work, and whale and fish detection and distribution analyses. Denise Risch is a central member of the NEFSC team, which also includes several NOAA-sponsored Hollings Scholars and graduate students. Dr. Leila Hatch oversees the SBNMS's project responsibilities, including hiring of the vessel and staff, scheduling of MARU field work, analysis of AIS data and other vessel GPS data, analysis of DTAG data, website and case study development and producing annual and final reports. Michael Thompson and Dr. Danielle Cholewiak are central members of the SBNMS team.

WORK COMPLETED

Since December 2007, consecutive arrays of MARUs have been deployed to record continuously at 2 kHz for 90-100 days in geometries designed to detect, localize and track vocally-active whale and fish

species during time periods of local abundance within sanctuary waters. Additional oceanographic data collected by CTD during each deployment and retrieval, data from transmission loss/calibration experiments, and analyses-in-progress are compiled and updated via a project-wide, internet-accessible database system.

Field experiments were conducted (5 October 2008 and 18 July 2009) to empirically measure and more accurately model sound transmission loss (TL) within the array area. Analyses and comparison of acoustic data to different sound propagation models was undertaken in AIM, focusing on shallow-water conditions. MARU received sound levels (RLs, dB re 1 µPa) were measured for 3rd octave bands using LTSpec, a customized tool written in Matlab (Cortopassi 2007). Playback source levels (SLs, dB re 1 µPa) were calculated for 6 different frequencies. All measurements were corrected for background noise. Additional field and laboratory efforts were undertaken to more extensively calibrate the equipment used in sound production, recording and acquisition.

Analysis efforts in 2008-9 expanded a framework initially developed in 2007-8 to integrate results from whale detection/localization/tracking, ship tracking, MARU RLs and physical environmental variables (wind, sediment type, CTD etc.). AIM was used to create predicted species-specific RL gridded surfaces throughout greater Mass Bay over the course of a month based on multiple empirical datasets. The 90x90 gridded modeling area covered 10,980 km^2 (90 km latitude, 122 km longitude).

RLs at MARU locations were calculated for species-specific frequency bandwidths (i.e., right whale contact calling, 71-224 Hz) and three 3rd octave bandwidths (centered at 20, 100, and 800 Hz). Spectrum statistics were computed as 5th, 25th, 50th, 75th and 95th percentiles using LTspec. For 10-minute data samples recorded at the MARUs nearest to two oceanographic buoys in Mass Bay (GMOOS A01 and NDBC 44013) in April 2008, 5% RL thresholds in the 71-224 Hz band were regressed against recorded wind speeds (meters/second per 10-minute). The resulting relationship was used to estimate wind-generated noise throughout the modeling area.

Whale and fish detection analyses continued with the implementation and further development of species-specific automatic detector tools. Data collected between December 2007 and May 2008 were used to build and test the efficiency of detectors for minke whale pulse trains as well as fin and humpback whale song. All automatic detectors, including the one previously developed for right whale up-calls (ISRAT, Urazghildiiev & Clark 2006), were run on data from April 2008. Data from July 2008 were used to identify non-song calls for humpback whales to enable improved characterization of species presence during the summer months when foraging is predominant and singing is minimal within SBNMS. XBAT and the Correlation Sum Estimation (CSE) Tool (Fristrup & Cortopassi unpublished) were used compute locations (x, y) of calling fin and right whales in December 2007-April 2008. Localization of right whale up-calls was used to identify the spatial and temporal characteristics of vocalizing groups (termed ‘acoustic groups’) present within the array. SLs for up-calls from acoustic groups located in April 2008 were calculated in AIM using their RLs and locations.

April 2008 MARU-derived acoustic detections of right whales were integrated with April 2008 visual sightings from NOAA Northeast Fisheries Science Center’s aerial survey efforts to create a course estimate of density and distribution of calling right whales within greater Mass Bay. AIM was used to model the acoustic movement of these right whales as “animats” [1], with calling intervals and SLs informed by MARU-located acoustic groups. The total area modeled was subdivided to create

[1] Animats are artificial animals with positional and movement data governed by AIM parameters (Frankel et al. 2003).

localized regions with perpetual lower and higher right whale densities, based on the observed acoustic and visual detections. AIM was then applied to generate a month-long 10-minute time-series of RLs from calling right whales within the 71-224Hz band over the gridded surface.

All AIS data collected in 2008 were analyzed to determine the number, size, type/cargo, and identity of vessels transiting the sanctuary using methods described in Hatch et al. (2008). Closest points of approach (CPAs) to MARUs were determined for all AIS-tracked vessels transiting greater sanctuary waters in April 2008. For ships passing <5km from MARUs, RLs were calculated for the right-whale low-frequency band (71-224 Hz) and AIM was applied to calculate vessel SLs. For ships passing >5km from MARUs, SLs from previously measured, same type vessels (Hatch et al. 2008) were used. AIM was applied to predict the time-series of RLs from each AIS-tracked vessel within the 71-224Hz band over the gridded surface. Matlab was used to sum all vessel noise fields and to create a gridded surface representing the total noise budget from large commercial ships. Finally, Matlab was used to sum the calling right whale, shipping noise and wind-generated noise gridded surfaces to create an empirically-based, 10-minute resolution animation of total noise throughout the modeled area.

An index of right whale communication masking representing the portion of the whale's communication space that is unavailable for communication was developed (Clark et al. in press) and implemented for April 2008 within greater Mass Bay. For each receiver grid point in the modeled area (n=8100) and for each 10-minute sample (n=4320), the index was calculated as the relative difference between the communication space available to all calling right whales under wind-generated noise and the communication space available to all calling right whales under conditions of wind-generated noise plus noise from large commercial shipping.

General levels of calling activity, represented by numbers of right whale calls detected per MARU, were compared to ambient noise measurements. Continuous MARU data for the month of April were divided into 15-minute bins (n=2880) and RLs for the 30-1000Hz, 30-400Hz and 3rd octave bands were calculated for each MARU using LTspec. Numbers of right whale up-calls were quantified in 15-minute bins for each MARU. All detected calls were reviewed by hand to remove false detections.

The tracking tool ISRAT_LT (Urazghildiiev unpubl.) was used to create predicted tracks of acoustic groups based on the timing of located calls and known right whale swimming speeds. AIM was used to estimate RLs from AIS-tracked commercial ships at locations where acoustic groups were located.

RESULTS

Observed RLs from a TL experiment were compared to those predicted by three models of sound propagation (Bellhop, Kraken and Parabolic Equation)[2]. The PE model (PE version 5.0, Zingareli et al. 1999) was found to best replicate the observed data. In addition, range-averaging (Harrison and Harrison 1995) was implemented to evaluate correspondence between observed vs. predicted measurements within 3rd octave bands (Figure 1). As seen in Figure 1, range-averaged PE was found to simulate the sound propagation characteristics of the SBNMS with a high degree of accuracy.

Figure 2 shows the distribution of AIS-tracked large commercial vessels in April 2008 within the modeling area. Of the 144 unique vessels identified, 33% were tugs/tows, 23% were cargo ships, 22%

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[2] Additional AIM parameters included NOAA's 3 arc-second bathymetry database, Consolidated Bottom Loss Upgrade (CBLUG) with Class 2 setting, and a wind speed of 10 knots.

were tankers, 16% were law enforcement, military, construction or research vessels, 4% were fishing boats and 4% were cruise ships, pleasure craft, ferries or sailboats[3]. Thirty of the 144 vessels had insignificantly contributions to RLs in the modeling area. Thus, the transiting activity of 114 vessels was modeled, with 50 vessels passing within 5km of MARUs.

Fin, right, and humpback whales were detected every day within the April 2008 MARU array (Figure 3). While no minke whales were detected, additional analyses have demonstrated generally low levels of acoustic detections for this species from December through April, with peaks during August and September. Acoustic time-bearing tracks for right whales were generated for each day during the December 2007-March 2008 deployment, for a total of approximately 60 groups. Multiple right whale acoustic groups were distinguished based on the location and timing of calls. For example, 296 located calls were grouped into 23 different acoustic groups on 1 April 2008. AIM estimated the average SLs for located right whale contact calls to be 163 dB (SD +/- 4 dB) within the 71-224Hz band.
Figure 4 shows an example of the time-varying 20, 100, 800 and 71-224Hz 3rd octave RLs based on 10-minute samples throughout April 2008 at a single MARU location. Regression analysis found a linear relationship between wind (m/s) and the 5th percentile RL, with a slope 0.1644 and intercept 96dB.

Figure 5 shows the month-long summation of 10-minute predicted RLs for the 90x90 receiver grid due to wind, calling right whales, transiting large commercial vessels and the total. The calling behavior and movements of 113 right whales were modeled based on visual sightings that ~1/3rd of the total North Atlantic right whale population was present in greater Mass Bay in April 2008. Figure 5 shows that shipping noise dominated the total accrued RLs for April 2008. Two 10-minute snapshots from the summed RL gridded surfaces (wind, calling right whales and shipping noise) are depicted in Figure 6. The relative difference in communication space available to calling right whales during times with fewer ships (Figure 6 left) versus more ships (Figure 6 right) is visually apparent here. This relative difference is quantified by calculating the communication masking index for the entire modeling area (Figure 7). For 25% of the month, communication masking was 0.05 or lower, representing conditions close to pre-shipping ambient levels. For 50% of the month, communication masking was greater than 0.69, representing a loss of ~70% of the communication space that calling right whales would have had without shipping. That loss was as great as 86% for 25% of the month. These results likely represent a conservative estimate of the situation facing communicating right whales in this region.

Figure 8 shows results from preliminary analyses of right whale calling-level response to noise based on a single MARU over the month of April 2008. Average ambient noise levels were 105.4 ± 5.3dB re: 1µPa (min: 96.2dB, max: 133.2 dB). Overall, 10% of the time periods had RLs ≤ 100dB re: 1µPa (n=277 bins), while 2% of the time periods had RLs > 120dB (n=58 bins). A total of 5420 right whale calls were detected on this channel in 25% of the 10-min samples (ca. 180 hours with detections). Calling activity varied from 0 - 43 calls per sample, with an average of 1.9 ± 4.5 calls/sample. Data from the first week of April were examined using cross-correlation analyses to investigate the relationship between numbers of calls and ambient noise measurements over 8 hour time lags. Correlation values were 0.1 or less, which was not considered to be significant. Ambient sound level data in the 30-400Hz band and right whale calling data are being as input to a time series model to determine whether calling activity varied under different noise conditions.

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[3] Because AIS carriage A requirements do not mandate transmitters for craft < 300 gross tons or with <165 passengers, these estimates underestimate the distributions and densities of small and mid-size vessels in the modeled area (i.e. fishing boats, pleasure craft and ferries).

Figure 9 shows preliminary results from the integration of a right whale acoustic group track and an AIS-tracked cargo ship (MV Teng He). AIM calculated a maximum RL of 105dB re: re: 1µPa for the acoustic group during the ship's passage. Possible changes in movement and vocalization behavior of acoustic groups relative to RLs from nearby ships are now being evaluated.

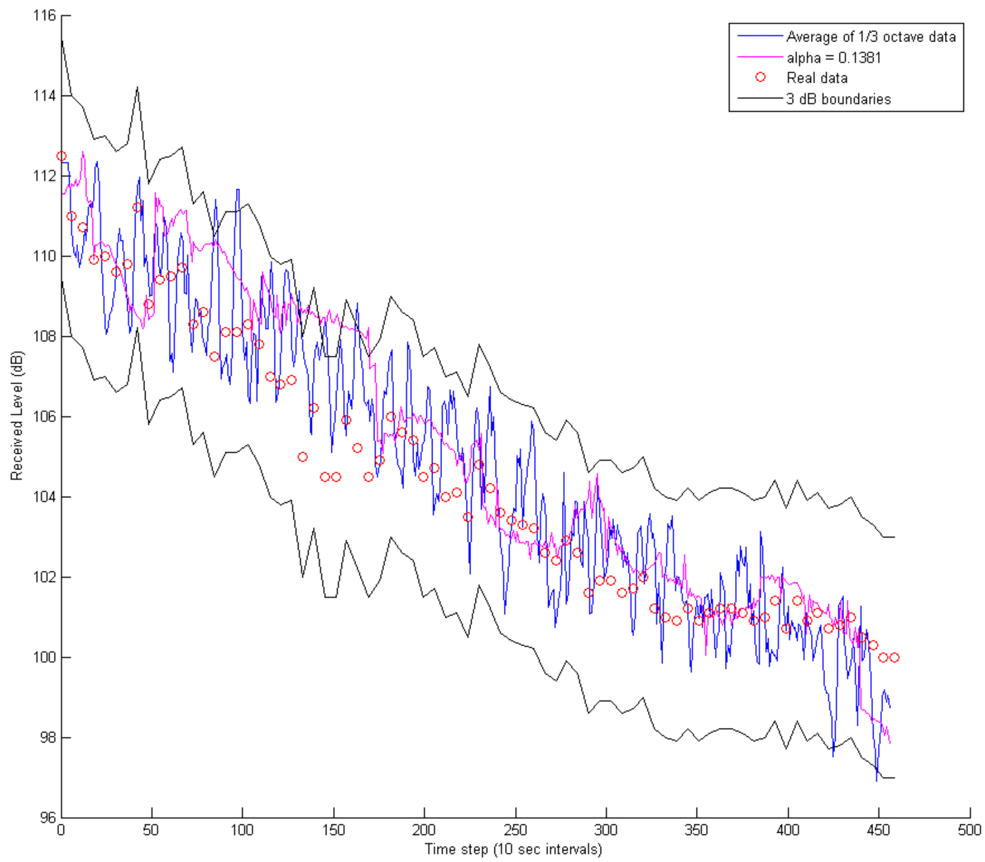

Figure 1. Comparison of 10-second 100Hz 3rd octave empirical MARU RLs (red dots) and AIM-predicted (Parabolic Equation Model) RLs for the 83 minute period following the close approach of the M/V Everlast on 27 December 2007. 100 Hz single frequency propagation modeling shows considerable variation (blue line), while range-averaged predictions for the 100Hz 3rd octave band (magenta line) show less variation and are a better match to the measured data. Notice that the range-averaged data almost always fall within 3 dB of the measured data (black lines).

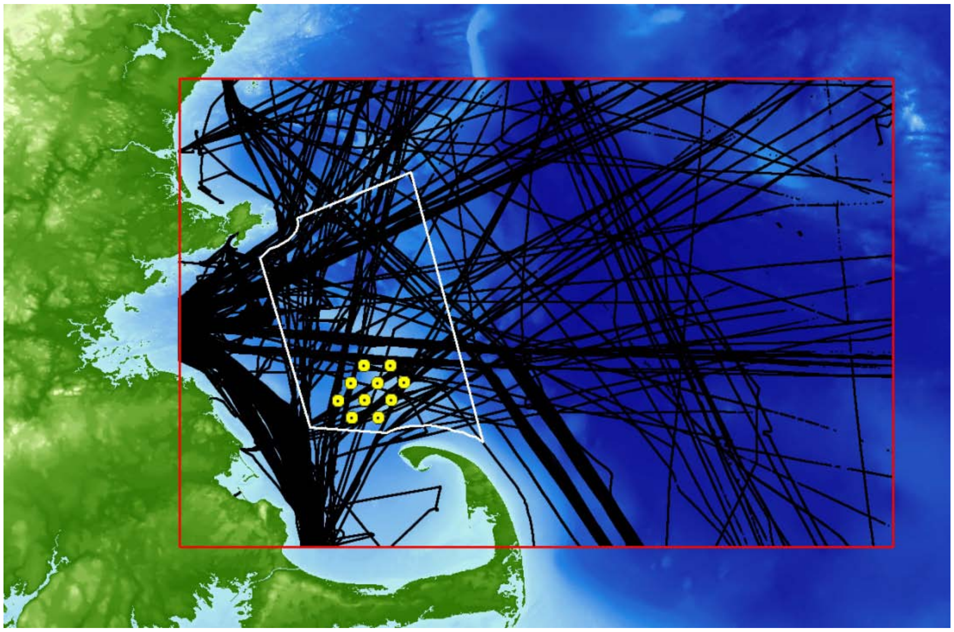

Figure 2. Distribution of 144 AIS-tracked large commercial vessels (black lines) that transited the modeling area (red boundaries) in April 2008. The locations of the bottom-mounted MARUs that were recording during this period (yellow dots) and the boundaries of the Stellwagen Bank National Marine Sanctuary (white) are also indicated.

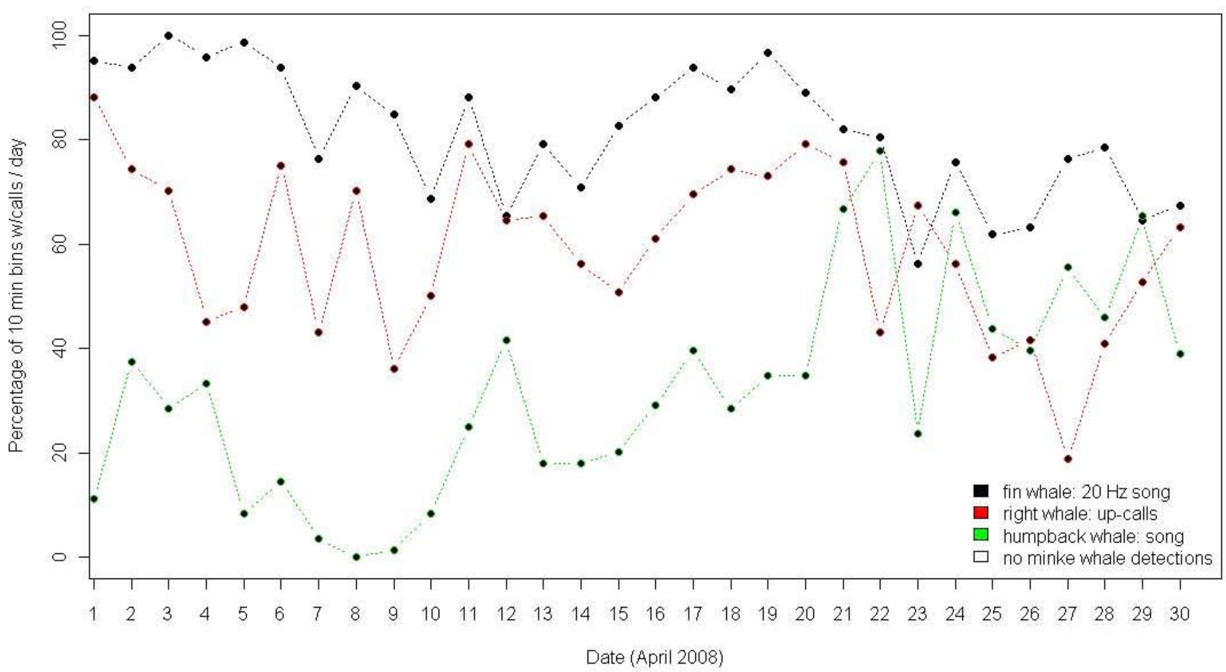

Figure 3. The percentages of 10-minute bins per day throughout the month of April 2008 in which North Atlantic fin, right, and humpback whales were acoustically detected on a single MARU within the array shown in Figure 2. No minke whale calls were detected during this month.

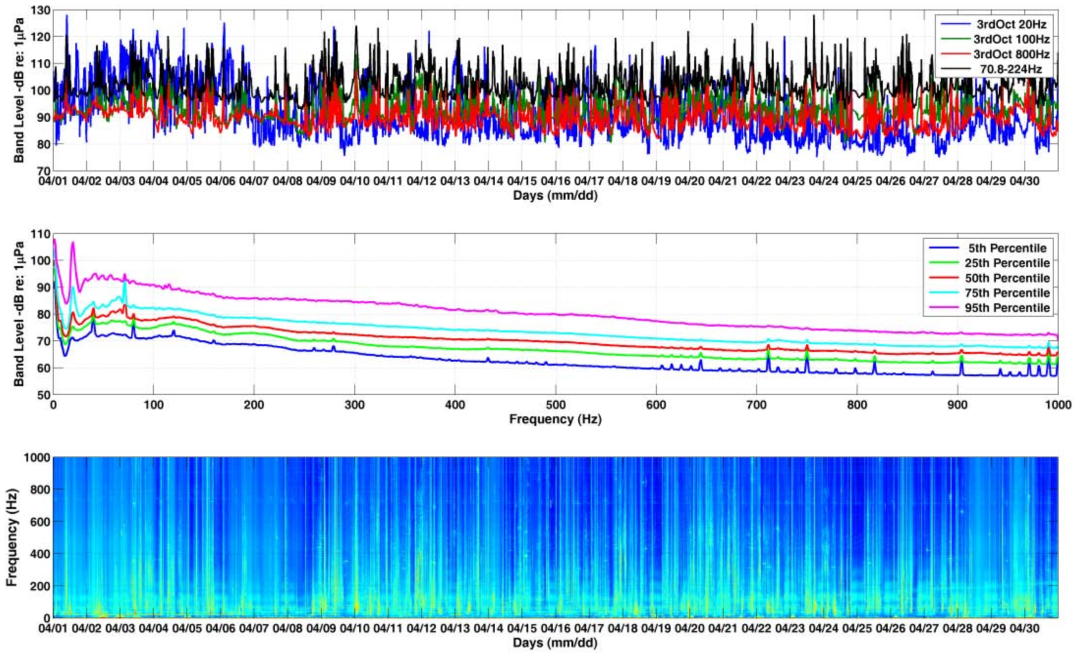

Figure 4. Received sound levels (20, 100, 800 and 71-224Hz 3rd octave bands; dB re 1μPa), percentages of time above several received level thresholds, and spectrogram for the month of April 2008 at a single MARU within the array shown in Figure 2.

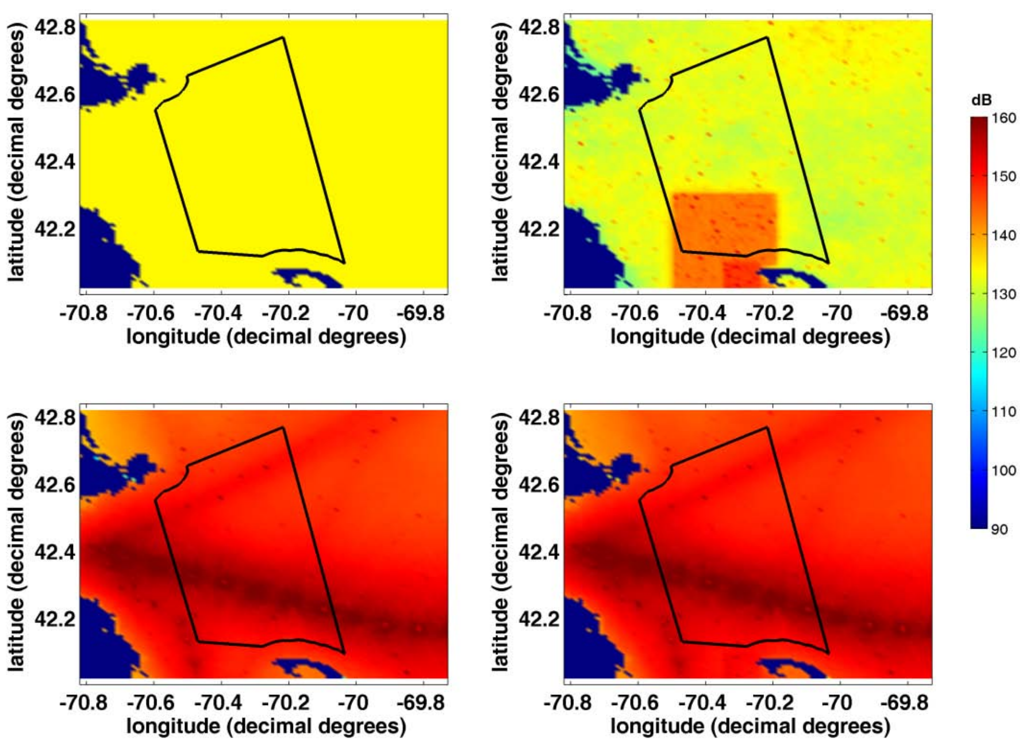

Figure 5. Summation of month-long (April 2008) contributions to total predicted RLs (71-224Hz, dB re 1μPa) due to wind-generated noise (top left), calling right whales (top right), AIS-tracked large commercial ships (bottom left and all three sources (bottom right.)

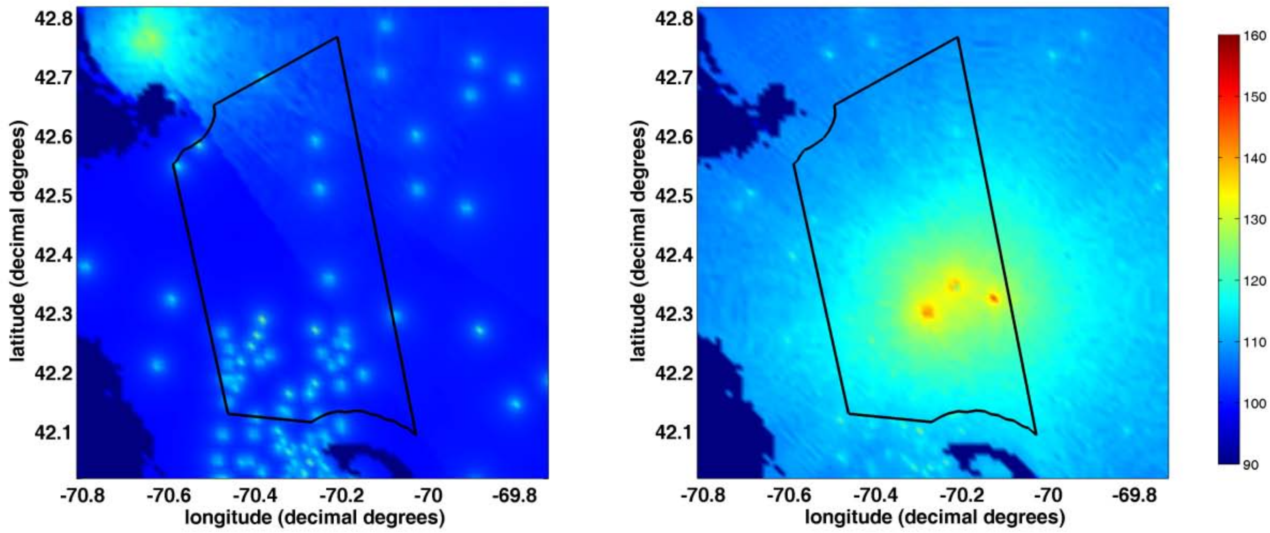

Figure 6. 10-minutes snap shots of received sound levels (71-224 Hz, dB re 1µPa) in the modeling area during a time with one distant (left) versus three central (right) AIS-tracked commercial ships.

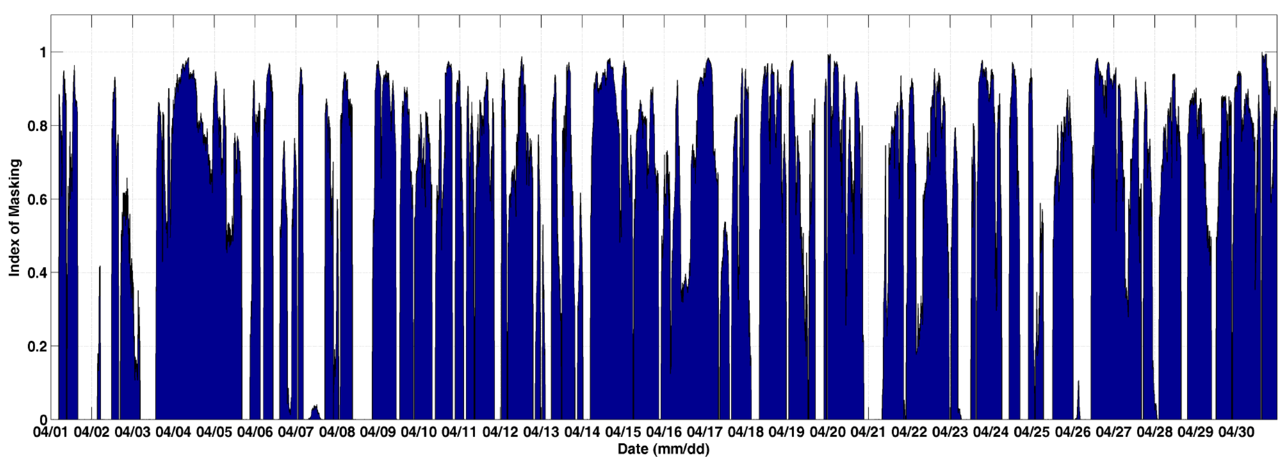

Figure 7. Right whale communication masking index within the modeling area calculated every 10-minutes during the month of April 2008, where 0 indicates no masking relative to a noise level of 75 dB in the 71-224Hz band and 1 indicated 100% masking as a result of noise from commercial vessels.

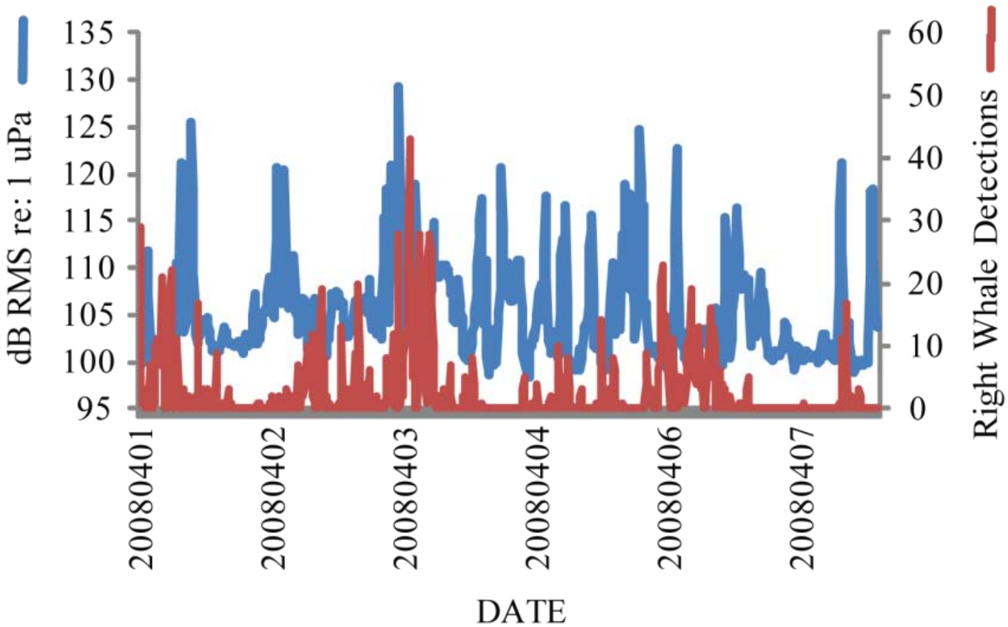

Figure 8. Received sound levels (blue, 30-400Hz dB re 1µPa) and numbers of detected right whale calls (red) for 15-minute time bins recorded on a single MARU in the array (Figure 2) on 1-7 April 2008.

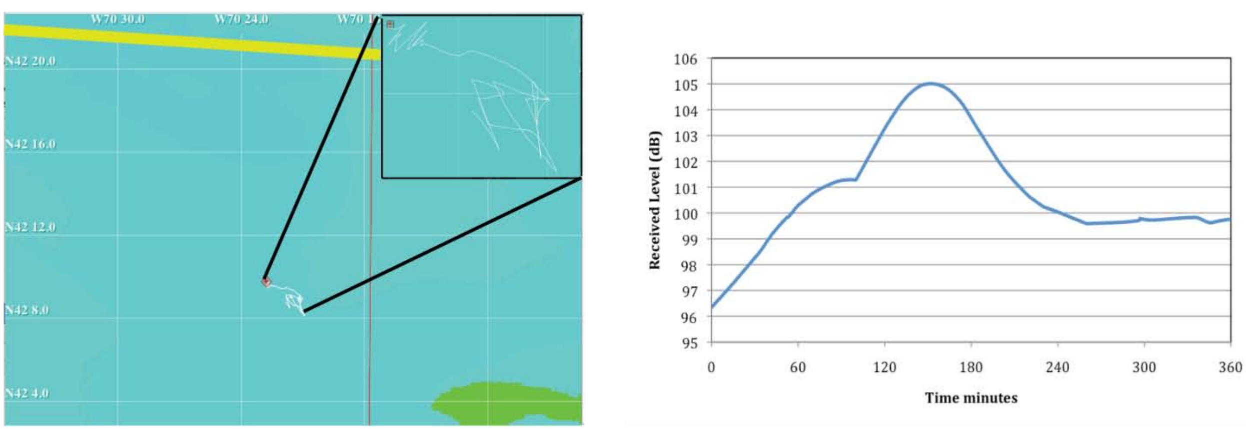

Figure 9. The track of a right whale acoustic group (left, inset) relative to the AIS-track of cargo ship M/V Teng He (left, yellow line), and the AIM-predicted received sound levels experienced by the acoustic group during the passage of the ship on 3 April 2008 (right.)

IMPACT AND APPLICATIONS

National Security

The Stellwagen NOPP Project is producing a suite of transferable tools for assessing contributions from several sources of noise to the underwater noise budget in an area of interest. These tools are valuable for assessing and contextualizing the place-based environmental impacts of defense-related activities, including training range development, sonar use, and high-density vessel activities.

Quality of Life

By describing changes in the acoustic environment of marine animals over biologically-relevant scales and assessing the impacts of these changes on marine animals this project will better inform managers and the general public on decisions regarding how best to minimize and/or mitigate the costs of human activities that introduce noise into the coastal environment. Tools created as part of the Stellwagen NOPP can be used by various stakeholders (i.e., governmental agencies, ocean user groups, environmental consultants, environmental advocacy organizations, and private citizens) to ensure that chronic, sub-lethal anthropogenic impacts associated with human noise-generating activities (i.e. shipping noise) are included in national, regional and international marine spatial planning initiatives.

Science Education and Communication

Upcoming forums that will showcase the Stellwagen NOPP project include the 18th Biennial Conference on the Biology of Marine Mammals (Quebec City, Quebec; October 12-16 2009) and the Minerals Management Service-sponsored "Workshop on the Status and Applications of Acoustic Mitigation and Monitoring Systems for Marine Mammals" (Boston, MA; November 17-19, 2009). Three invited papers to be included in a theme section of the *Marine Ecology Progress Series* entitled "Applications of Acoustics in Exploring Marine Ecosystems and the Impacts of Anthropogenic Sound" (expected publication late fall-winter 2009-10) will highlight results from this NOPP research.

TRANSITIONS

National Security

Quality of Life

Methodologies being developed for the Stellwagen NOPP Project are also being used to evaluate impacts associating with the construction and operation of two offshore liquefied natural gas terminals adjacent to the SBNMS. As the contractor responsible for evaluating the acoustic impacts of these terminals and as a result of this NOPP-funded research, Cornell is developing new ways of calculating and articulating the contributions of multiple types of noise sources to the noise budgets in the sanctuary and surrounding waters. Additional contracts to provide passive acoustic monitoring in Arctic waters coincident with seismic exploration for oil and gas resources have also received the benefit of these NOPP tool developments.

Science Education and Communication

The sanctuary's website continues to be supplemented to provide information on the project and on noise in the marine environment (http://stellwagen.noaa.gov/science/passive_acoustics.html). In 2009, materials from the Stellwagen NOPP Project were included in the "Oceans Today Kiosk", part of the Smithsonian National Museum of Natural History's new Oceans Hall. Project PIs also hosted a symposium at the International Marine Conservation Congress (Washington, DC; May 2009) entitled "An Ocean Noise Forum: Passive Acoustic Technologies, Impacts and Solutions for The Marine Environment". This symposium was focused on the use of passive acoustic tools in marine conservation research and management and highlighted examples from the Stellwagen NOPP project. Project PIs and a colleague from the NOAA Ocean Acoustic Program (NMFS S&T) served as

panelists. The symposium attracted 60+ attendees from groups as diverse as the U.S. House of Representatives, Resources Committee, NSF, US Navy, the World Shipping Council, CORE, IUCN, NRDC and numerous academic and industry scientists who are leading the development of new relationships, partnerships, and recognitions through group discussions and recommendations for ways forward. Additional 2009 domestic and international ocean noise policy forums that highlighted the Stellwagen NOPP Project case study include the International Conference on Marine Mammal Protected Areas (Maui, Hawaii; March 2009), the 157th Meeting of the Acoustical Society of America (Portland, Oregon; 18-22 May 2009), the 61st meeting of the International Whaling Commission's Scientific Committee (Madeira, Portugal; 31 May – 12 June 2009), the National Meeting of Marine Mammals (Santa Domingo, Dominican Republic; 29 June 2009), Okeanos Workshops on Cumulative Impacts to Marine Mammals from Noise and Alternatives to Airguns for Seismic Exploration (Monterey, CA; August-September 2009), and the 4th International Workshop on the Detection, Classification and Localization of Marine Mammals Using Passive Acoustics (Pavia, Italy; 10-13 September 2009).

RELATED PROJECTS

The Stellwagen NOPP Project is related to two database development projects, one cumulative impact mapping project and one population modeling project. Sofie Van Parijs and Denise Risch provided OBIS-SEAMAP (http://seamap.env.duke.edu/) with an acoustic data set which is going to set the precedent for integrating acoustics into this database. This project will come on line later this year. NOPP acoustic data will be integrated when OBIS-SEAMAP is ready to receive it. Dr. Clark (Cornell) is collaborating with Dr. Andrew Pershing (University of Maine/Gulf of Maine Research Institute) to facilitate the use of passive acoustic data from the Stellwagen NOPP project in the Whale Habitat Informatics Project (WHIP, http://gmri.org/whales/). The Massachusetts Oceans Partnership is engaged in mapping the annual cumulative impacts of human activities on the marine environment from the Commonwealth's shoreline to the boundaries of the US Exclusive Economic Zone (200 nm offshore). Through collaboration with researchers based at the National Center for Ecological Synthesis and Analysis (NCEAS; Santa Barbara, CA), information from the Stellwagen NOPP project is informing a preliminary representation of the input of noise from large commercial shipping in these maps. Finally, following initial discussion at an Okeanos-sponsored workshop in August 2009, Stellwagen NOPP project PIs are engaged in a working group to create a model of the population consequences of noise on feeding North Atlantic right whales using data collected in Massachusetts Bay (including NOPP project data).

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